cold working such as cold rolling about 2 or 3 or 9 or 10%, preferably about 4 or 5% to about 7 or 8%, can improve strength while retaining good toughness. Yield strength can be increased around 10 ksi, for instance to levels as high as around 59 or 60 ksi or more without excessively degrading toughness, even actually increasing toughness by 5 or 6 ksi$\sqrt{\text{in}}$ (K_c in L-T orientation), in one test by stretching 6 or 7%.

When referring to a minimum (for instance for strength or toughness) or to a maximum (for instance for fatigue crack growth rate), such refers to a level at which specifications for materials can be written or a level at which a material can be guaranteed or a level that an airframe builder (subject to safety factor) can rely on in design. In some cases, it can have a statistical basis wherein 99% of the product conforms or is expected to conform with 95% confidence using standard statistical methods.

Fracture toughness is an important property to airframe designers, particularly if good toughness can be combined with good strength. By way of comparison, the tensile strength, or ability to sustain load without fracturing, of a structural component under a tensile load can be defined as the load divided by the area of the smallest section of the component perpendicular to the tensile load (net section stress). For a simple, straighT-sided structure, the strength of the section is readily related to the breaking or tensile strength of a smooth tensile coupon. This is how tension testing is done. However, for a structure containing a crack or crack-like defect, the strength of a structural component depends on the length of the crack, the geometry of the

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structural component, and a property of the material known as the fracture toughness. Fracture toughness can be thought of as the resistance of a material to the harmful or even catastrophic propagation of a crack under a tensile load.

Fracture toughness can be measured in several ways. One way is to load in tension a test coupon containing a crack. The load required to fracture the test coupon divided by its net section area (the cross-sectional area less the area containing the crack) is known as the residual strength with units of thousands of pounds force per unit area (ksi), When the strength of the material as well as the specimen are constant, the residual strength is a measure of the fracture toughness of the material. Because it is so dependent on strength and geometry, residual strength is usually used as a measure of fracture toughness when other methods are not as useful because of some constraint like size or shape of the available material.

When the geometry of a structural component is such that it doesn't deform plastically through the thickness when a tension load is applied (plane-strain deformation), fracture toughness is often measured as plane-strain fracture toughness, K_{Ic}. This normally applies to relatively thick products or sections, for instance 0.6 or 0.75 or 1 inch or more. The ASTM has established a standard test using a fatigue pre-cracked compact tension specimen to measure K_{Ic} which has the units ksi$\sqrt{\text{in}}$. This test is usually used to measure fracture toughness when the material is thick because it is believed to be independent of specimen geometry as long as appropriate standards for width, crack length and thichness are met. The symbol K, as used in K_{Ic}, is referred to as the stress

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intensity factor. A narrower test specimen width is sometimes used for thick sections and a wider test specimen width for thinner products.

Structural components which deform by plane-strain are relatively thick as indicated above. Thinner structural components (less than 0.6 to 0.75 inch thick) usually deform under plane stress or more usually under a mixed mode condition. Measuring fracture toughness under this condition can introduce variables because the number which results from the test depends to some extent on the geometry of the test coupon. One test method is to apply a continuously increasing load to a rectangular test coupon containing a crack. A plot of stress intensity versus crack extension known as an R-curve (crack resistance curve) can be obtained this way. The load at a particular amount of crack extension based on a 25% secant offset in the load vs. crack extension curve and the crack length at that load are used to calculate a measure of fracture toughness known as K_{R25}. It also has the units of ksi$\sqrt{\text{in}}$. ASTM E561 (incorporated by reference) concerns R-curve determination.

When the geometry of the alloy product or structural component is such that it permits deformation plastically through its thickness when a tension load is applied, fracture toughness is often measured as plane-stress fracture toughness. The fracture toughness measure uses the maximum load generated on a relatively thin, wide pre-cracked specimen. When the crack length at the maximum load is used to calculate the stress-intensity factor at that load, the stress-intensity factor is referred to as plane-stress fracture toughness K_c. When the stress-intensity factor is calculated using the

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crack length before the load is applied, however, the result of the calculation is known as the apparent fracture toughness, K_{app}, of the material. Because the crack length in the calculation of K_c is usually longer, values for K_c are usually higher than K_{app} for a given material. Both of these measures of fracture toughness are expressed in the units ksi$\sqrt{\text{in}}$. For tough materials, the numerical values generated by such tests generally increase as the width of the specimen increases or its thickness decreases.

It is to be appreciated that the width of the test panel used in a toughness test can have a substantial influence on the stress intensity measured in the test. A given material may exhibit a K_{app} toughness of 60 ksi$\sqrt{\text{in}}$ using a 6-inch wide test specimen, whereas for wider specimens the measured K_{app} will increase with wider and wider specimens. For instance, the same material that had a 60 ksi$\sqrt{\text{in}}$ K_{app} toughness with a 6-inch panel could exhibit a higher K_{app}, for instance around 90 ksi$\sqrt{\text{in}}$, in a 16-inch panel and still higher K_{app}, for instance around 150 ksi$\sqrt{\text{in}}$, in a 48-inch wide panel test and still higher K_{app}, for instance around 180 ksi$\sqrt{\text{in}}$, with a 60-inch wide panel test specimen. Accordingly, in referring to K values for toughness herein, unless indicated otherwise, such refers to testing with a 16-inch wide panel. However, those skilled in the art recognize that test results can vary depending on the test panel width and it is intended to encompass all such tests in referring to toughness. Hence, toughness substantially equivalent to or substantially corresponding to a minimum value for K_c or K_{app} in characterizing the invention products, while largely referring to a test with a 16-inch panel, is intended to embrace variations in K_c or K_{app} encountered in using different width

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panels as those skilled in the art will appreciate. The testing typically is in accordance with ASTM E561 and ASTM B646 (both incorporated herein by reference).

Resistance to cracking by fatigue is a very desirable property. The fatigue cracking referred to occurs as a result of repeated loading and unloading cycles, or cycling between a high and a low load such as when a wing moves up and down or a fuselage swells with pressurization and contracts with depressurization. The loads during fatigue are below the static ultimate or tensile strength of the material measured in a tensile test and they are typically below the yield strength of the material. If a crack or crack-like defect exists in a structure, repeated cyclic or fatigue loading can cause the crack to grow. This is referred to as fatigue crack propagation. Propagation of a crack by fatigue may lead to a crack large enough to propagate catastrophically when the combination of crack size and loads are sufficient to exceed the material's fracture toughness. Thus, an increase in the resistance of a material to crack propagation by fatigue offers substantial benefits to aerostructure longevity. The slower a crack propagates, the better. A rapidly propagating crack in an airplane structural member can lead to catastrophic failure without adequate time for detection, whereas a slowly propagating crack allows time for detection and corrective action or repair.

The rate at which a crack in a material propagates during cyclic loading is influenced by the length of the crack. Another important factor is the difference between the maximum and the minimum loads between which the structure is cycled. One measurement including the effects of crack length and the difference between maximum

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and minimum loads is called the cyclic stress intensity factor range or ΔK, having units of ksi√in, similar to the stress intensity factor used to measure fracture toughness. The stress intensity factor range (ΔK) is the difference between the stress intensity factors at the maximum and minimum loads. Another measure affecting fatigue crack propagation is the ratio between the minimum and maximum loads during cycling, and this is called the stress ratio and is denoted by R, a ratio of 0.1 meaning that the maximum load is 10 times the minimum load.

The crack growth rate can be calculated for a given increment of crack extension by dividing the change in crack length (called Δa) by the number of loading cycles (ΔN) which resulted in that amount of crack growth. The crack propagation rate is represented by Δa/ΔN or 'da/dN' and has units of inches/cycle. The fatigue crack propagation rates of a material can be determined from a center cracked tension panel.

Still another technique in testing is use of a constant ΔK gradient. In this technique, the otherwise constant amplitude load is reduced toward the latter stages of the test to slow down the rate of ΔK increase. This adds a degree of precision by slowing down the time during which the crack grows to provide more measurement precision near the end of the test when the crack tends to grow faster. This technique allows the ΔK to increase at a more constant rate than achieved in ordinary constant load amplitude testing.--

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